PRECISION MEASUREMENTS OF THE CMB POWER SPECTRUM

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Abstract

Within the next 5–10 years it will be possible to make precision maps of the CMB from both sub-orbital and orbital experiments. Maps covering a significant portion of the sky at high sensitivity and small beam sizes ($\ll$ horizon size at decoupling) will, in theory, allow for the extraction of fundamental cosmological parameters. These measurements of the CMB power spectrum promise to revolutionize our understanding of the early universe.

1 Introduction

Potentially, studies of the Cosmic Microwave Background (CMB) angular power spectrum can provide some of the most precise determinations of the fundamental cosmological parameters we can make. These measurements are also among the most difficult and challenging to make and we will have to await the next generation of experiments to see if the promise is fulfilled. The simplest fundamental assumptions made over half a century ago about a homogeneous and isotropic universe are still consistent with our current knowledge of the universe. We now know from studies of the CMB that the assumption of isotropy is valid to an astonishing level, one which has profoundly affected the theoretical concepts of how we view the very early universe. Our field has historically been one where even upper limits on detections could profoundly affect the theoretical framework. It is only in the past few years that this has changed from strict upper limits to hints of detection in 1991 to detection of structure and the beginning of measurements of the power spectrum today. We now have a rudimentary knowledge of the CMB power spectrum sufficient to constrain and even make preliminary measurements of the fundamental parameters such as total density, baryon fraction, etc. The challenge in the coming 5-10 years will be to extend these measurements to large sky coverage and broader frequency coverage with beam sizes substantially smaller than 1 degree. Given the extremely small level of signal we have to contend with and the potential for systematic error, the convergence of a number of experiments will be required. Combining maps of the CMB with maps from other surveys, such as optical and IR LSS surveys, will provide a database we could only dream about even a decade ago. The potential for knowledge is enormous and while potential pitfalls are possible, we are much more confident today than we were even 5 years ago based on recent measurements.

2 Approaches to the Problem

Discovery comes awkwardly at first in many fields and it is no less true in this one. Not knowing the amplitude or shape of the power spectrum or the precise form of the galactic and extragalactic foregrounds has made our task that much more difficult. The experimental response has largely been to try many different experiments over a large angular and frequency range. We now have reasonably good agreement on the measurements and feel optimistic that we are truly measuring the cosmological power spectrum. If we concentrate on the degree scale and below measurements, we find a highly varied approach experimentally. Ground based and balloon borne systems have very different atmospheric emission and other systematic errors. For example, the atmospheric emission at 40 GHz varies from 10 K at some low ground based sites to 5 K at the South Pole to less than 1 mK at balloon altitudes. At 200 GHz ground based sites are extremely difficult to use for anisotropy measurements and even balloon borne measurements suffer from some non-trivial atmospheric contamination at the higher frequencies. In spite of the atmospheric emission sub orbital approaches have produced by far the most sensitive measurements, indeed our 1991 ground based measurements at the South Pole still have the smallest errors per pixel. This is in spite of the fact that the atmosphere is more than 5 orders of magnitude larger than the cosmological signal. Ideally we would like to map the CMB with infinite signal to noise and infinitely small beam size, i.e. make a "pencil beam" survey. In practice however we will have to incrementally approach the problem, rather than have one "ultimate" experiment. With at least two space missions now planned, MAP in the US and COBRAS-SAMBA in Europe, and possibly RELICT-II in Russia, spaced based observations will be well represented. The MAP mission may produce data as early as 2002 while the COBRAS-SAMBA mission would be a few years later. Ground based and balloon-borne measurements will also vigorously be pursued with very exciting results expected within a few years.

3 Balloon Borne Missions

The primary differences between a terrestrial and an orbital mission fall into several distinct areas. The main differences are the addition of the atmosphere as a source of emission, side-lobe instrument response reduction in extended orbit missions, possible reduction in optics temperature in orbit and the ability to make a more uniform dataset from space.

3.1 Atmosphere

The atmosphere effects a mission in a number of ways. The primary effect is that the atmosphere emits ,and absorbs, millimeter wavelength radiation in a complicated way depending on the wavelength and pressure and temperature profile in the air. The primary atmospheric constituents that are responsible are O_2, O_3 and H_2O. Many other molecular species exist but in general are not significant for us. Pressure broadening of the lines is such that at sea level the emission spectrum is a "blur" of the individual lines into a slowly changing (in wavelength) continuum of emission. At high altitudes the pressure broadening is small enough that the individual lines become distinct and the ratio of the peak to the valley, where the tails of distinct lines meet, in the line spectra becomes very large. In Figure 2 we show an example of the atmospheric emission at low and high altitudes. At sea level the typical emission in the wavelength range of interest (1–10 mm) is several to many times the CMB itself. There is little distinct line emission apparent except near the 60 GHz oxygen cluster and a few other lines. At high altitudes available to balloons the emission is distinctly line-like with peak to valley ratios exceeding 1000 and a overall reduction from sea level emission in the most favorable windows of 10^4 from 10 K to 1 mK or even less. Note however that this kind of reduction is only possible for very narrow band systems that can observe between the lines. This is a distinct advantage of narrow band coherent systems, HEMTs for example, over broad band incoherent systems (bolometers). The situation becomes even worse at high frequencies as the flux (or equivalent antenna temperature) of the CMB becomes smaller as shown in Figure 2. Indeed, an interesting comparison is that our HEMT measurements at 30 GHz at the South Pole, 4 Km, had comparable atmospheric emission to the bolometric emission at balloon altitudes (35 Km) at 200 GHz, whereas our HEMT observations at balloon altitudes were a factor of 1000 lower. This is of fundamental importance to our ability to make 2-D maps from balloon altitudes with HEMTs. For the very sensitive instruments we now have, another aspect of observing through the atmosphere becomes important, namely "atmospheric noise". There are three issues here. The first is that the atmosphere increases the total effective system noise since the atmosphere adds a background (shot noise). The second is that the atmosphere varies both temporally and spatially. The third is that beam chopping through the atmosphere will add noise unless the beam precisely repeats its position. For example, a 1 arc second error in beam elevation will introduce a signal of 7T microK where T is the vertical atmosphere in Kelvin. There are two cases of interest here. One is that the instrument may oscillate slightly, as certainly occurs in balloon borne instruments. A one arc-minute amplitude oscillation would give a 400T microK amplitude signal. This is not negligible. A typical pendulation amplitude of 1 arc-minute would give such an amplitude. The vertical atmospheric emission (T) depends on the observing band and altitude. As mentioned above, this number can be of order 1 mK for HEMTs and 0.1–1 K for bolometers which for a 1 arc-minute pendulation would give a signal of 0.4 microK for a HEMT and 40–400 microK for a bolometer based experiment. This can be a critical issue for bolometer experiments. A related issue is the "altitude noise" of the instrument. In particular, the instrument will have short term variation in the elevation position due to excitation of various modes in the balloon, flight train and payload. An amplitude of 10–60 arc seconds is not atypical. This can add noise as well as an aliased signal. The level of noise and signal is a complicated function of the sampling, scan, excitation modes and pendulation frequency. The very low level of the atmospheric emission for balloon borne HEMT measurements makes possible a 2 dimensional scan mode that allows a map to be directly generated. This is the basis for our balloon borne ACE experiment, for example.

3.2 Sidelobes

The small level of the cosmological signal requires extremely good rejection of other sources of millimeter radiation. There are a number of sources to be concerned about. These include the earth, moon, sun, atmosphere and galaxy as the dominant contributors. The earth is the primary problem for most of the relevant experiments. With an effective temperature near 300

K and a desired instrument sensitivity of 10 microK rejection of the earth of $> 10^8$ is desired. In terms of antenna response the relevant factor is the comparison between the main beam size, assume it to be 10 arc minutes, and the solid angle of the earth, (2π steradians). This gives another factor of 10^6. Therefore, ideally, we would like to reject the earth at a level of $> 10^{14}$ or 140 db. This is nearly an impossible number to achieve in practice and indeed is overly pessimistic. The reason is that the earth does not present a unity contrast target for the system and that the chopped response is far less. Indeed in our tests of the ACME instrument to detect earth sidelobe emission *in situ* by looking close to the horizon we have not been able to detect it except at extremely small angles near the horizon. It is also important to note that to mimic a cosmological signal the earth signal would have to change at the celestial rate or be aliased into it.

3.3 Optics Temperature Issues

At balloon altitudes the typical air temperature is $-20°$ to $-50°$ C. In low earth orbit radiatively cooled optics reach 100 K depending on the shielding and in far earth orbit (e.g., L2) optics temperatures of 50 K are possible. The typical emissivity of aluminum is $7 \times 10^{-4} \cdot (\text{Freq}/100\ \text{GHz})^{1/2}$. This is based on bulk aluminum conductivity and measured in flight performance at 90 GHz. At frequencies substantially higher than 100 GHz emissivities rise well above this, so that 1% emissive surfaces are not unheard of at sub-millimeter wavelengths. If we assume 0.1% emissivity, for a 100 GHz receiver, and balloon optics an effective optics emission of 200 mK is reasonable per mirror surface. To be able to resolve 10 microK cosmological signals places a requirement on the allowed synchronous optics temperature variation of $< 0.01°$ C. With 1% emissive optics this would be $< 0.001°$ C. Again the fact that the cosmological signal varies at the sidereal rate helps us as does a rapid chop. In a space environment the fact that there is no air makes this issue easier to deal with.

3.4 Data Uniformity

One of the difficulties we have had in sub-orbital measurements is the piecing together of different datasets to draw global conclusions. Some of the scatter we see in the present power spectra measurements is no doubt due to this problem and to the issue of varying systematics and calibrations between experiments. This is a key area where a single space based experiment will have an enormous advantage over sub-orbital measurements. Very long duration balloon experiments will also have some of this advantage. Sub-orbital experiments can overcome some of this limitation by restricting the power spectra estimates to higher "l" where these issues are less critical. *In situ* calibration is also important to tie together non-uniform datasets.

4 Current Status

4.1 Early Power Spectrum Estimates

We now know we had detected degree scale structure and had a preliminary measurement of power spectrum prior to COBE announcement in 1992, though like any new result it required confirmation. Subsequent measurements by us and others showed that our earlier measurements were indeed consistent. Prior to the COBE launch in 1989, our Advanced Cosmic Microwave Explorer (ACME) payload had made two balloon flights and one South Pole expedition making measurements from 0.3 to 3 degrees with SIS and bolometric detectors. Prior to the April 1992

COBE announcement, ACME had flown four times and made two South Pole trips with a total of seven measurements. Our 1988 South Pole trip with ACME outfitted with a sensitive SIS (Superconductor-Insulator-Superconductor) receiver resulted in an upper limit at 0.5° of $\Delta T/T \leq 3.5 \times 10^{-5}$ at 0.5° for a Gaussian sky. This was very close to the "minimal predictions" of anisotropy and, as we were to subsequently measure, just barely above the level of detectability. In the Fall of 1989, we had our first ACME-MAX flight with a subsequent flight the next summer (so-called MAX-II flight). This flight resulted in structure being detected consistent with a cosmological origin. This data was taken in a low dust region and showed no evidence for galactic contamination. This data in the Gamma Ursa Minoris region ("GUM data") was first published in Alsop et al. (1992)[3] *prior* to the COBE detections. At the time, our most serious concern was of atmospheric stability, so we revisited this region in the next ACME flight in June 1991. In the meantime, ACME was shipped to the South Pole in October 1990 for more ground based observations, this time with both an SIS detector and a new and extremely sensitive HEMT (High Electron Mobility Transistor) receiver. At scales near 1°, close to the horizon size, results from the South Pole using the ACME with a HEMT-based detector place an upper limit to CMB fluctuations of $\Delta T/T \leq 1.4 \times 10^{-5}$ at 1.2° (Gaier et al., 1992).[4] This upper limit for a Gaussian auto correlation function sky was computed from the highest frequency channel. This data set however has significant structure in excess of noise. Because the beam size varies inversely as the frequency and because of the "step scan" used, a "negative effective" spectral index is expected. Without more data the spectral information was ambiguous. Under the assumption that the structure seen is cosmological, a four-channel average of the bands yields a detection at the level of $\Delta T/T = 1 \times 10^{-5}$. This is consistent with the signal measured in an adjacent strip in SP91 (Schuster et al. 1993) as well as measured subsequently in the SP '94 dataset in another adjacent strip. Analysis of dust and synchrotron maps from the area of the sky surveyed, with reasonable assumptions about the spectral indices, predict that the signal level we observed is not consistent with expected dust or synchrotron.

Additional analysis of the 1991 ACME South Pole data using another region of the sky and with somewhat higher sensitivity shows a significant detection at the same level of $\Delta T/T = 1 \times 10^{-5}$ (Schuster et al., 1993).[5] Again, the low frequency synchrotron maps do not show similar morphology and would predict an amplitude that is much smaller (< 7 μK). The amplitude is also inconsistent with known dust emission. No evidence for point source contamination was found either. The 1σ error measured per point in this scan is 14 μK or $\Delta T/T = 5 \times 10^{-6}$. Per pixel, this is the most sensitive CMB measurement to date at any angular scale. The relevant measurements just prior to the COBE announcement are summarized in Fig. 1. While this early data was quite confusing at the time, particularly the rise in the power spectrum from 1.5 to 0.5 degrees, it is now seen with our additional measurements to be consistent with a similar rise now seen in the Sasskatoon data. The large angular scale data was provided by the COBE data in 1992, and as shown in Fig. 5, the earlier degree-scale measurements are consistent with the COBE detections.

4.2 Recent Results

The recent Sasskatoon 95 data, SK95, support the rise in the power spectrum seen in the earlier ACME data, though with a somewhat higher overall normalization. However the SK 95 data has an overall 30% uncertainty in calibration and hence it cannot be yet concluded if there is any discrepancy. Very recently the CAT interferometer results at l=400-600 combined with the degree scale measurements tentatively show that there is a fall in the power spectrum at large "l" with a peak somewhere around l=200-300. This is consistent with the other upper limits at large "l". The new SK 95 data also support this conclusion. With refined results at l=100-500

Figure 1: ACME CMB power spectrum data prior to the COBE detection. Theoretical curves are from Steinhardt and Bond (private communication). See KEY in Fig. 5 caption.

from ground and balloon data expected in the next few years, we will get good estimates of Ω and the baryon fraction.

5 Foreground Issues

In the microwave region, the primary extraterrestrial foreground contaminants are galactic synchrotron and thermal bremsstrahlung emission. Below 50 GHz, both of these contaminants have significantly different spectra than CMB fluctuations. Because of this, multi frequency measurements can distinguish between foreground and CMB fluctuations (provided there is large enough signal to noise).

Above 50 GHz, the primary contaminant is interstellar dust emission. At frequencies above 100 GHz, dust emission can be distinguished from CMB fluctuations spectrally, also using multi frequency instruments.

At all observation frequencies, extragalactic radio sources are a potential concern. Extragalactic radio sources have the disadvantage that there is no well-known spectrum which describes the whole class of sources. For this reason, measurements over a very large range of frequencies and angular scales are required for CMB anisotropy measurements in order to achieve a sensitivity of $\Delta T/T \approx 1 \times 10^{-6}$. As we proceed towards smaller beams sizes the problem becomes progressively more difficult for point source contamination. However as we

Figure 2: Relevant backgrounds for terrestrial measurements at the South Pole and at balloon altitudes (35 km). Representative galactic backgrounds are shown for synchrotron, bremsstrahlung, and interstellar dust emission as well as the various ACME (center) wavelength bands.

Date	Site	Detector System	Beam FWHM (deg.)	Sensitivity
1988 Sept	Balloon[P]	90 GHz SIS receiver	0.5	4 $mKs^{1/2}$
1988 Nov-1989 Jan	South Pole	90 GHz SIS receiver	0.5	3.2
1989 Nov	Balloon[FS]	MAX photometer (3, 6, 9, 12 cm^{-1}) ^3He	0.5	12, 2, 5.7, 7.1
1990 Jul	Balloon[P]	MAX photometer (6, 9, 12 cm^{-1}) ^3He	0.5	0.7, 0.7, 5.4
1990 Nov-1990 Dec	South Pole	90 GHz SIS receiver	0.5	3.2
1990 Dec-1991 Jan	South Pole	4 Channel HEMT amp (25–35 GHz)	1.5	0.8
1991 Jun	Balloon[P]	MAX photometer (6, 9, 12 cm^{-1}) ^3He	0.5	0.6, 0.6, 4.6
1993 Jun	Balloon	MAX photometer (3, 6, 9, 12 cm^{-1}) ADR	0.55–0.75	0.6, 0.5, 0.8, 3.
1993 Nov-1994 Jan	South Pole	HEMT 25–35 GHz	1.5	0.8
1993 Nov-1994 Jan	South Pole	HEMT 38–45 GHz	1.0	0.5
1994 Jun	Balloon	MAX photometer (3, 6, 9, 14 cm^{-1}) ADR	0.55-0.75	0.4, 0.4, 0.8, 3.
1996 Feb	Balloon	HACME HEMT 38–45 GHz	0.7	0.4, 0.5, 0.8
1996 Jun	Balloon	HACME HEMT 38–45 GHz	0.7	0.4, 0.5, 0.8

Table 1: CMB measurements made with ACME.
Sensitivity does not include atmosphere which, for ground-based experiments, can be substantial.

P–Palestine, TX
FS–Fort Sumner, NM

show in Figures 2 the estimated contribution for 10' beam surveys is still encouraging. We can make an estimate of the portions of the sky that are likely to be contaminated by galactic emission by combining the low and high frequency galaxy maps with our "knowledge" of the spectral indexes of the various species. In Fig. 3, we show such an estimate for the fraction of sky uncontaminated by the direct emission from our galaxy. Keep in mind that this is only an estimate based on our present data. While additional galactic surveys would help to determine the galactic component better, it is assumed at the current time that the best data on galactic contamination will come from the future CMB maps themselves. Additional ground based surveys of point sources and H-II emission will be a great aid in CMB studies however. For our SP '94 data set we have made a point source survey at a number of frequencies to determine the spectra of the brightest point sources in our field (Gundersen et al., 1997). No evidence of significant point source contamination was found for this data set. Ideally, such point source surveys could be carried out for the entire sky. Such a task is daunting however considering the number of known, let alone unknown, point sources. For example, in ACME, the sensitivity to point sources is about 47 microK per Jansky at 40 GHz. This is for a 1 degree beam. A 10' beam size experiment will face a point source sensitivity of about 1 mK per Jansky. A 1 ppm per pixel survey of the CMB at 10' resolution will require milli-Jansky point source rejection ability.

A summary of the various observations with this instrument is given in Table 1.

6 ACME Results

There have been a total of 13 ACME observations/flights from 1988 to 1996. Over 20 articles and proceedings have resulted from these measurements as well as ninen Ph.D. theses. ACME-

Figure 3: Galactic model estimates for the fraction of sky uncontaminated below a given level. The model includes synchrotron, bremsstrahlung, and dust emission. The synchrotron model is given for two different spectral indices. Far off the galactic plane (where we are most interested in measuring), the steeper spectral index is more appropriate. The dust model is based on the IRAS 100 micron map combined with our dust data from the mu-Pegasus region.

Figure 4: Estimated cosmological parameter extraction uncertainty versus sensitivity

SIS and ACME-HEMT articles by Meinhold and Lubin (1991),[6] Meinhold et al. (1992),[7] Gaier et al. (1992),[4] Schuster et al. (1993),[5] Gundersen et al. (1995),[8] and ACME-MAX articles by Fischer et al. (1992),[9] Alsop et al. (1992),[3] Meinhold et al. (1993),[10] Gundersen et al. (1993),[11] Devlin et al. (1994),[12] Clapp et al. (1994)[13] Tanaka et al. (1996)(15) and Lim et al. (1996)(16) summarize the results to date.

7 Future

This is a particularly exciting time in our field as we are on the verge of making precision maps of the CMB at sub-degree scales over large regions of the sky. Within the next 3-5 years we will get data from balloon borne mapping instruments as well as ground based interferometers. The range from 0.1 - 10 degrees should be relatively well quantified over a large range of wavelengths. Although we have now made measurements sensitive enough to extract many of the cosmological parameters we lack the sky coverage to reduce the sample and cosmic variance to a reasonable level. We are now at a point, both technologically and in our understanding of the relevant CMB signals and non cosmological backgrounds, that we can seriously contemplate making a precision measurement of the CMB power spectrum. What is needed is not necessarily more sensitivity, though more is always welcome, but more samples of the sky. Some of the current and past confusion in measurements of the power spectrum are undoubtably due to small statistics. For example in Figure 4 we show the estimated cosmological parameter extraction precision versus beam size and pixel sensitivity for an experiment that cover 50% of the sky. While the extraction procedures and error estimates are still being debated, it appears feasible to get precision in measuring the various parameters to the percent level within the next decade. This implicitly assumes a cosmological model that is "well behaved" and assumes no additional pathological foregrounds. We will soon know if these are reasonable assumptions or not.

Figure 5: Recent ACME results (in BOLD) along with results from other groups. Key: a-COBE, b-FIRS, c-Tenerife, d1-SP91 9 pt. 4 channel analysis-Bond '93, d3-SP91 9+13 pt. 4 channel analysis-Bond '93, d5-SP91 9 pt. Gaier et al. '92, e-Big Plate, f-PYTHON, g-ARGO, h-MAX4-Iota Dra, i-MAX4-GUM, j-MAX4-Sig Herc, k-MSAM2, l-MSAM2, m-MAX3-GUM, n-MAX3-mu Peg, o-MSAM3, p-MSAM3, q-Wh. Dish, r-OVRO7, s2-SP94-Q, s3-SP94-Ka, t-SP89, u-MAX2-GUM, many from Steinhardt and Bond by private communication.

Publication	Configuration	Beam FWHM (deg.)	$\Delta T/T \times 10^{-6}$
Meinhold & Lubin '91	ACME-SIS SP '89	0.5	<35
Alsop et al., '92	ACME-MAX-II (GUM)	0.5	45^{+57}_{-26}
Gaier et al., '92	ACME-HEMT SP '91	1.5	<14
Meinhold et al., '92	ACME-MAX-III (μ Peg - upper limit)	0.5	<25
Meinhold et al., '92	ACME-MAX-III (μ Peg - detection)	0.5	15^{+11}_{-7}
Schuster et al., '93	ACME-HEMT SP '91	1.5	9^{+4}_{-2}
Gundersen et al., '93	ACME-MAX-III (GUM)	0.5	42^{+17}_{-11}
Devlin et al., '94	ACME-MAX-IV (GUM)	0.55-0.75	37^{+19}_{-11}
Clapp et al., '94	ACME-MAX-IV (Iota Draconis)	0.55-0.75	33^{+11}_{-11}
Clapp et al., '94	ACME-MAX-IV (Sigma Hercules)	0.55-0.75	31^{+17}_{-13}
Gundersen et al., '95	ACME-HEMT SP '94	1	$15^{+5.7}_{-2.5}$
Lim et al., '96	ACME-MAX-V (μ Peg)	0.5	<13
Tanaka et al., '96	ACME-MAX-V (HR5127)	0.5	12^{+4}_{-3}
Tanaka et al., '96	ACME-MAX-V (Phi Herculis)	0.5	19^{+7}_{-4}

Table 2: Recent ACME degree-scale results.

8 Mapping Techniques

To date, essentially all the sub degree experiments have been done in a one dimensional scan mode and have not been able to make a "true map". This has been done because of the atmospheric emission restricting us to make one dimensional, constant elevation angle chops. All of the ACME measurements are of this type. An orbital mission does not suffer from this problem, of course. However even then one is making 1-D strips and then "sewing" them together to make a map. The COBE mission was no exception. The only "real maps" so far have been made by interferometers, and then a "map" must be carefully scrutinized since the data weighting is far from uniform. With the exception of interferometers, experiments have been either differential or "total" power (this means a direct measure of the flux is made). Virtually all experiments (including our own) have opted for the differential technique as it is less demanding on various system stabilities. Recently experiments have shown that a direct "total" power measurement is possible and the era of sub-degree resolution maps is about to begin. It is easy to see why this is difficult. The typical equivalent noise of a state-of-the-art detector is 10–30K. This is to be compared to the desired sensitivity of 3–30 micro Kelvin. This requires a system stability of the order of 1-10 ppm.

9 Polarization

The CMB is characterized by the four Stokes parameters I, Q, U and V in each direction and at each frequency observed. I characterizes the overall spectrum (flux) while Q and U give the linear polarization and V the circular polarization. Very little effort has been directed towards the measurement of the polarization of the CMB compared to the effort in anisotropy detection. In part, this is due to the low level of linear polarization expected. Typically, the polarization is only 1–30% of the anisotropy and depends strongly on the model parameters. This is an area which, in theory, can give information about the reionization history, scalar and tensor gravity wave modes, and large-scale geometry effects. It is now possible to measure CMB polarization to a sensitivity of better than 1 ppm on limited portions of the sky. In the future, this may be a very fruitful area of inquiry, particularly when combined with overlapping anisotropy measurements. In particular the polarization-anisotropy cross correlation is a very powerful technique in understanding and breaking degeneracies in the parameter extraction. Dedicated polarization measurements designed to reach a level of sensitivity of 1 ppm or better are possible. At mm and cm wavelengths this is possible to do from the ground since the atmosphere is essentially unpolarized at these wavelengths.

10 Orbital vs. Sub Orbital Missions

There are currently several major proposed (and now started) satellite missions. The European COBRAS-SAMBA proposal is a combined HEMT and bolometer mission, and would cover from about 1 to 10 mm with resolution varying from about 4 to 40 arc minutes depending on the frequency. In the U.S., the Mid-Explorer class MAP mission is a HEMT based mission that will cover from 3 to 15 mm with a beam size from 20 to 60 arc minutes. There are significant differences in technical and programmatic approaches being taken with the European being a more ambitious, and hence, more costly experiment. The U.S. Mid-Explorer mission is designed with more limited objectives, but at a significantly lower price and at a possibly shorter time scale to launch. Either of these missions would provide invaluable data that could revolutionize our understanding about early universe physics. Currently, it can be assumed that these missions will not produce data before 2002 at the earliest for the US mission, and 2004 for the European one, and hence, it is to be anticipated that continued vigorous ground-based and suborbital experiments will continue to produce valuable data.

Indeed per pixel sensitivities with suborbital missions in the μK region are now achievable with current and new technologies, HEMTs, and bolometers over hundreds to hundreds of thousands of pixels and possibly over large portions of the sky. With the HEMT and bolometer array receivers that are being planned now for sub-orbital measurements, it is quite likely that the integrated sensitivity and resolution of these measurements will exceed that of the US mission. The major issue will be atmospheric stability, control of sidelobes and getting a uniform dataset. Ideally, to reduce systematic effects, full-sky coverage would be best, and this is one area where a space-based measurement will excel. In a number of ways the sub-orbital and orbital missions will be complimentary and allow for a very powerful combined dataset.

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References

[1] Lubin P. et al., 1985, Astrophys. J. **298**, L1.

[2] Pospieszalski, M. W. et al., 1990, IEEE MTT-S Digest, 1253

[3] Alsop, D. C. et al., 1992, Astrophys. J. **317**, 146

[4] Gaier, T. et al., 1992, Astrophys. J. **398**, L1

[5] Schuster, J. et al., 1993, Astrophys. J. **412**, L47

[6] Meinhold, P. R. and Lubin, P. M., 1991, Astrophys. J. **370**, L11

[7] Meinhold, P. et al., 1992, Astrophys. J. **406**, 12

[8] Gundersen, J. O. et al., 1995, Astrophys. J. **443**, L57

[9] Fischer, M. et al., 1992, Astrophys. J. **388**, 242

[10] Meinhold, P. et al., 1993, Astrophys. J. **409**, L1

[11] Gundersen, J. O. et al., 1993, Astrophys. J. **413**, L1

[12] Devlin, M. et al., 1994, Astrophys. J. **430**, L1

[13] Clapp, A. et al., 1994, Astrophys. J. **433**, L57

[14] Wollack, E. et al., 1994, Astrophys. J. **419**, L49

[15] Lim, M. et al., in press (1996).

[16] Tanaka, S. et. al., in press (1996).

[17] Smoot, G. F. et al., 1992, Astrophys. J. **396**, L1

[18] Gundersen, J. O. et al., 1997, to be submitted to Astrophys. J.